Measurement of Inclusive Charm Production in Two-Photon Collisions at LEP

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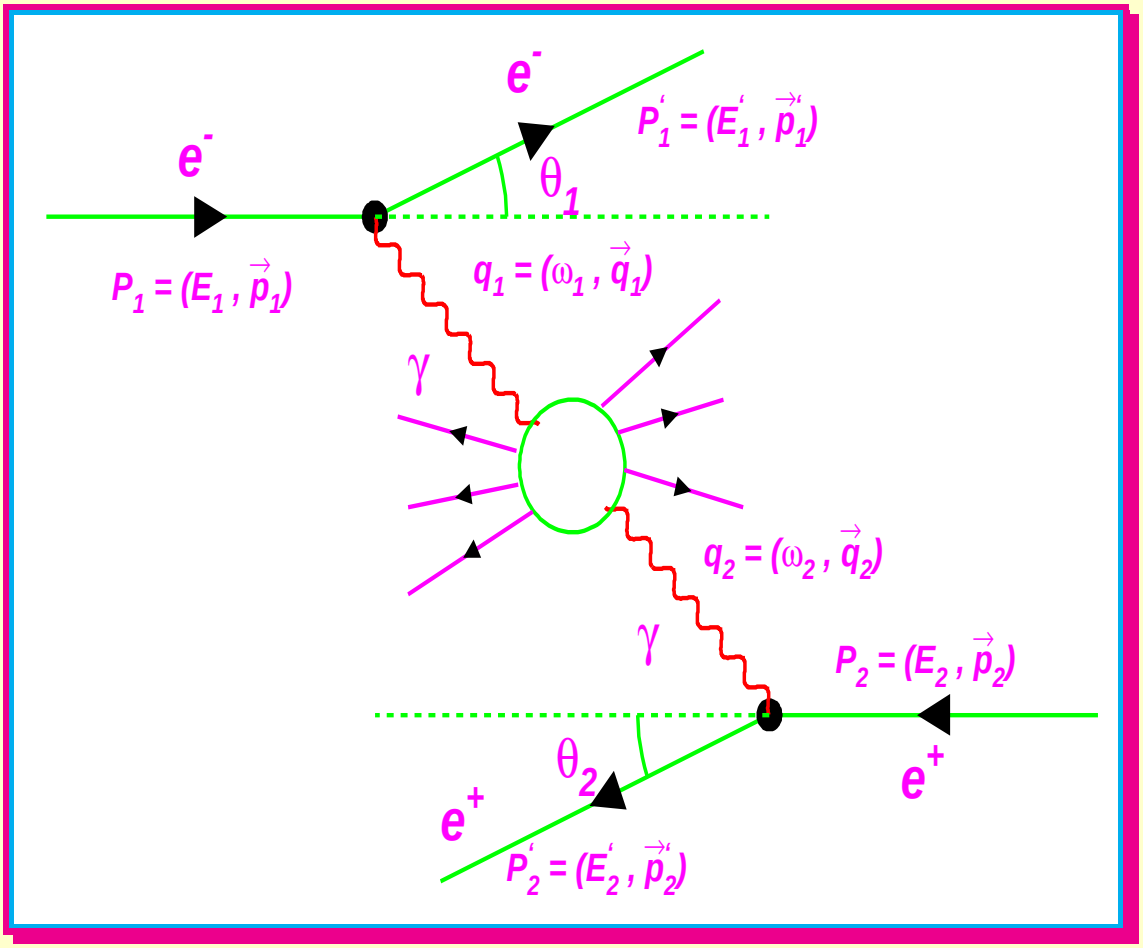
- Motivation
- Lepton Identification
- Heavy Flavor Production
- Direct & Resolved Processes
- Summary & Outlook

Two-Photon Interactions



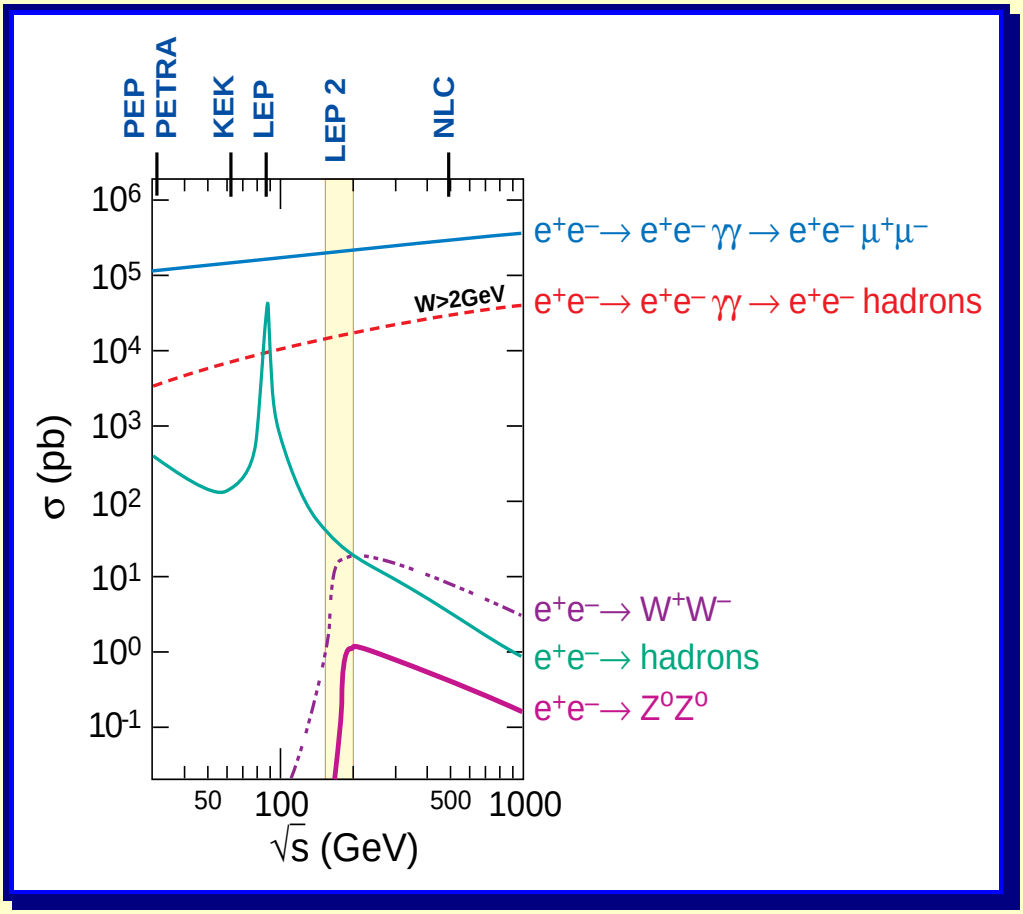
- $\mathbf{W^2_{\gamma\gamma} = (\sum_h E_h)^2 - (\sum_h \vec{p})^2}$

  Invariant mass is typically small in a e^+e^- collision compared to center-of-mass energy $\sqrt{s}$

- $\mathbf{Q^2_i = -q^2_i = 2E_iE'_i(1 - \cos\,\theta_i)}$

  Anti-tag condition ($Q_i^2 \approx 0$) real photons have a small transverse momentum, or virtuality

Two-Photon Interactions

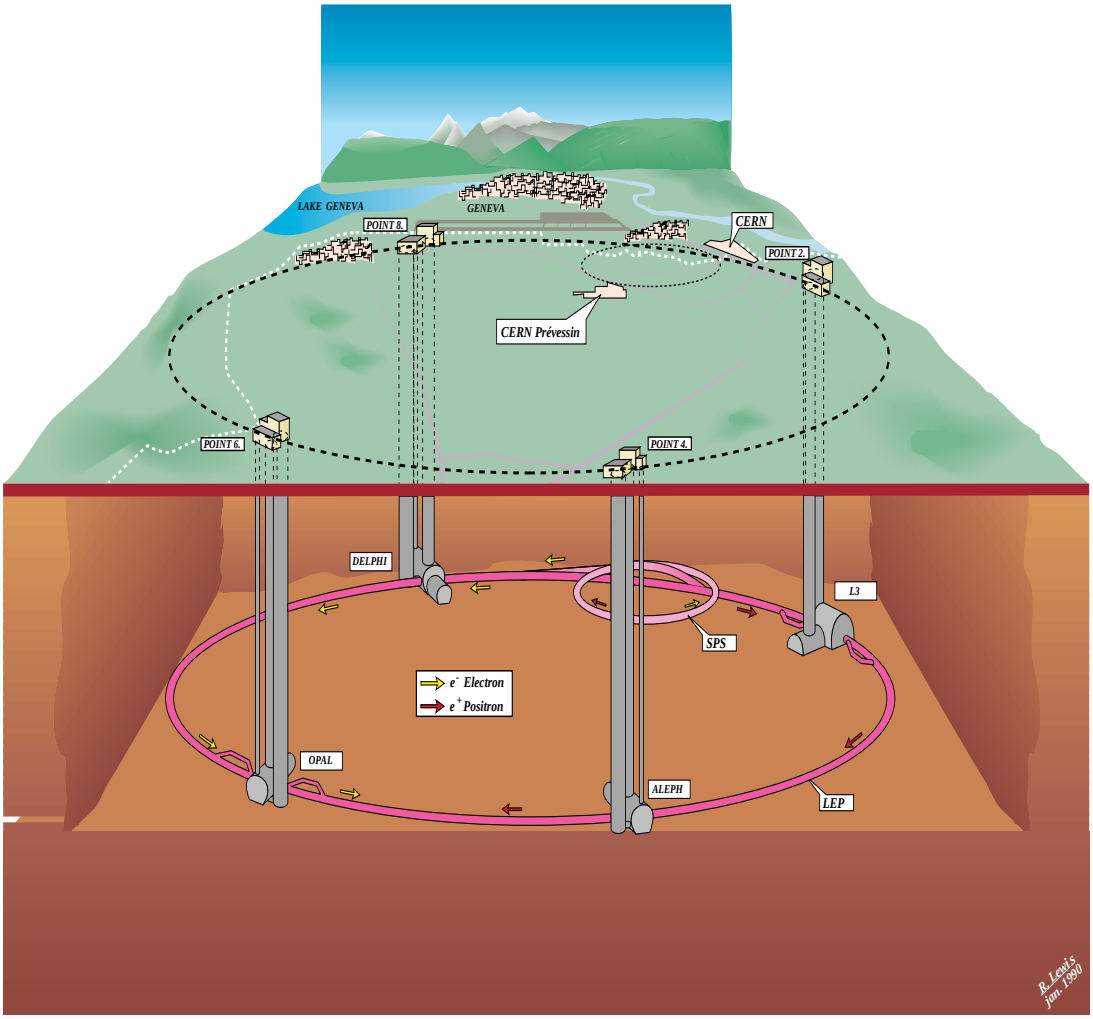


- **Annihilation Processes:**
  $\sigma(e^+e^- \to X) \propto 1/s$
  ...except resonance production such as Z^0

- **Two-Photon Processes:**
  $\sigma(e^+e^- \to e^+e^- X) \propto (ln(s/m^2_{elec}))^2$

- **Background to other processes.**

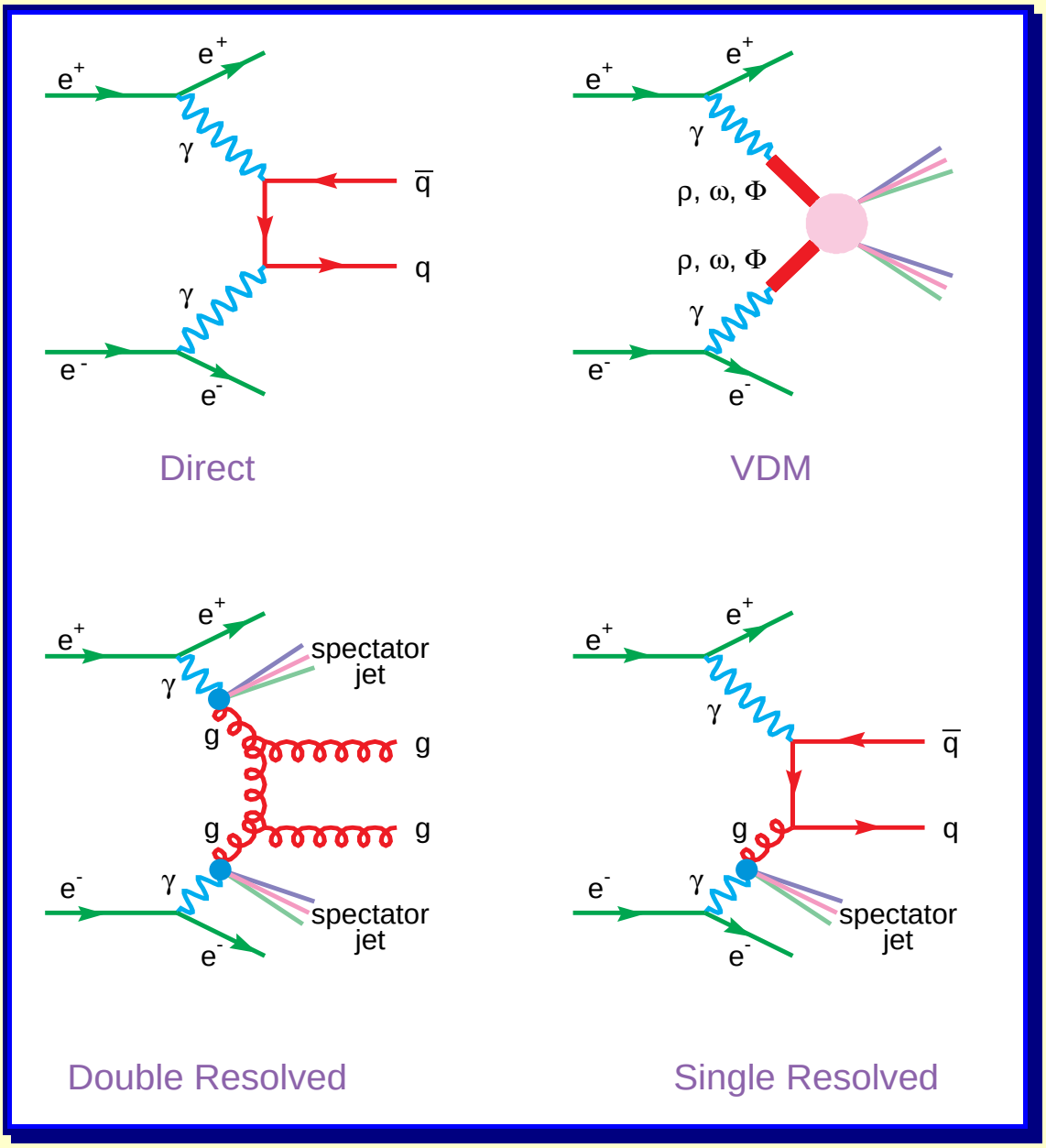
LEP Collider



ALEPH, DELPHI, L3, OPAL

- LEP1: 1989 - 1995 $\rightarrow \sqrt{s} \simeq 91$ GeV
- LEP2: 1996 - 2000 $\rightarrow \sqrt{s} = 130$ - 200 GeV
- Surpassed 200 pb^{-1} for the year 1999, with max. $\sqrt{s} \simeq 202$ GeV!
- $\mathcal{L} > 450\ \mathrm{pb}^{-1}$ to date Ahead of schedule!

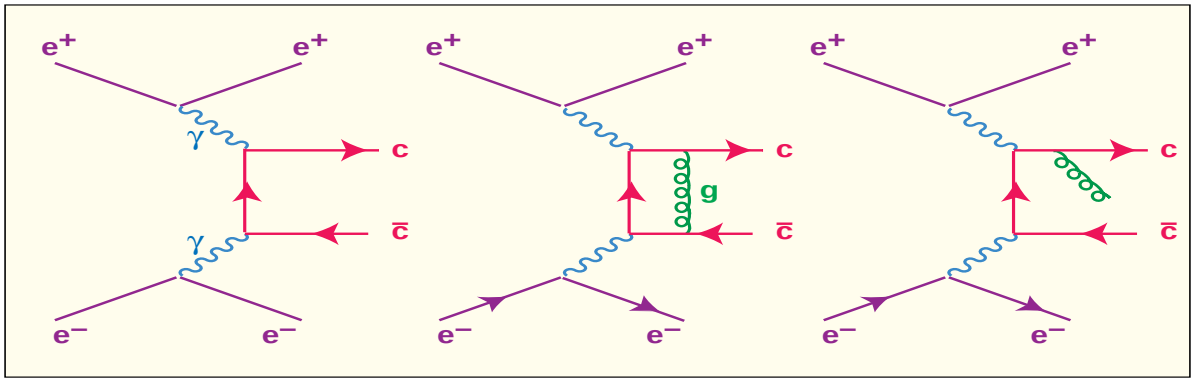
$\gamma\gamma$ Hadronic Production

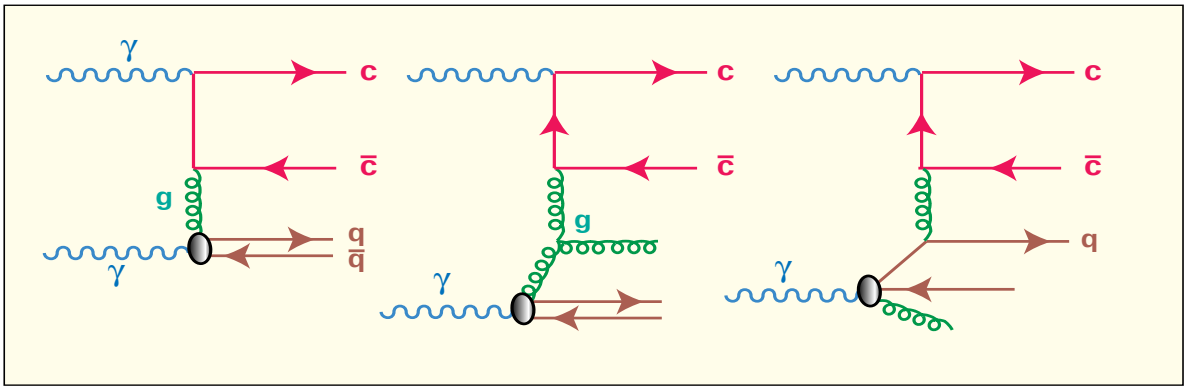


- **Direct and Single Resolved Processes dominant in $e^+e^- \to e^+e^-Q\bar{Q}$ production**

Heavy Flavor Production

Beauty production suppressed relative to charm due of smaller charge and larger mass



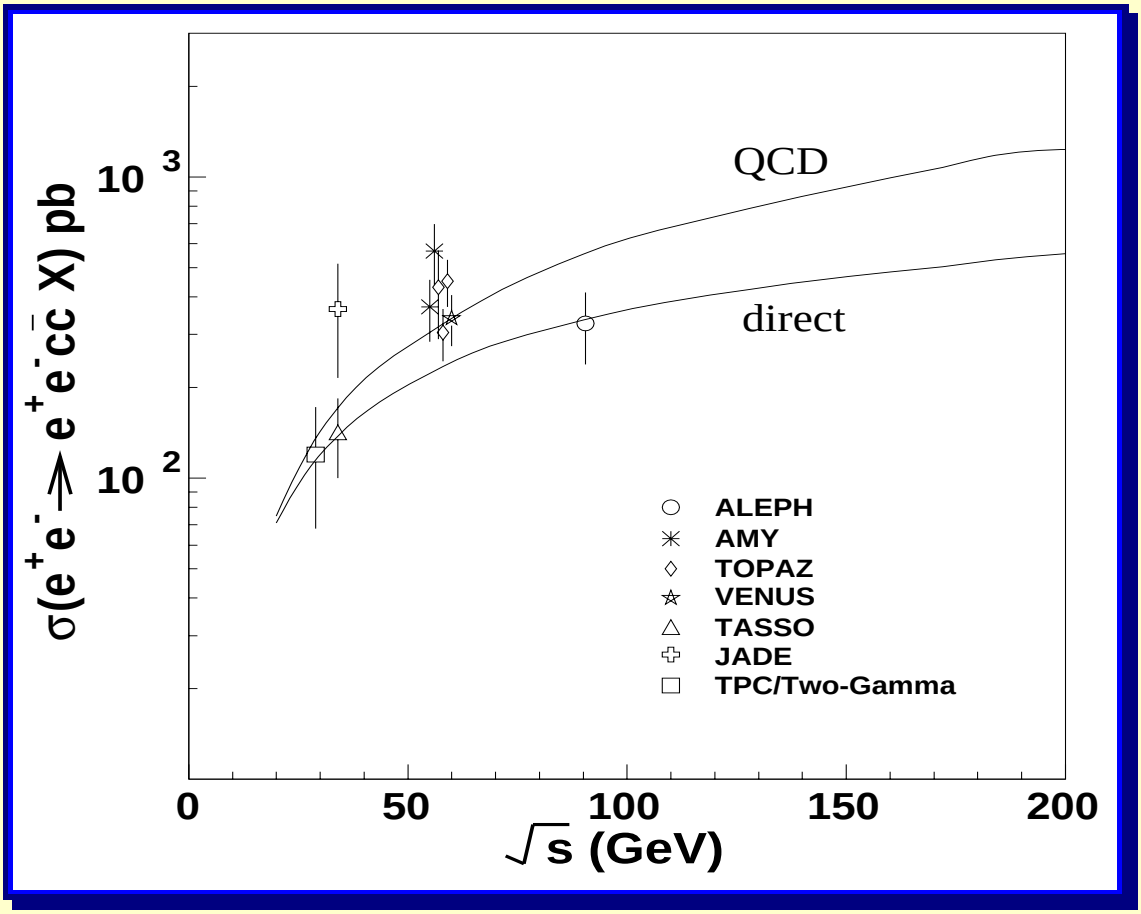


- **Direct process depends on m_c (m_b) and α_s**
- **Resolve process also depends on gluon content of the photon**

Contribution from Direct and Resolved processes are predicted to be comparable at LEP2 energies

Theoretical Cross Section

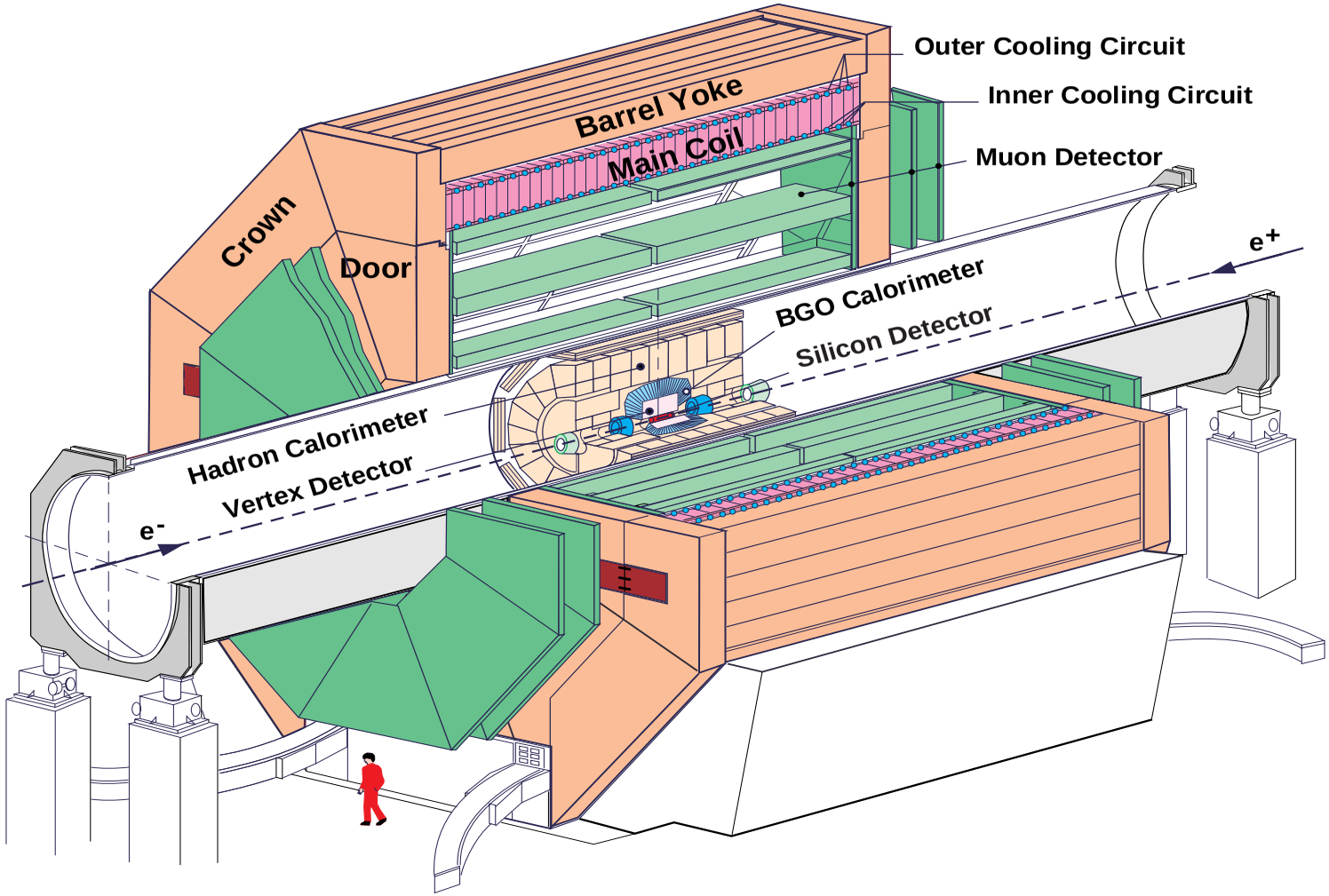
Next-to-Leading (NLO) Calculations



Ref: M.Drees, M.Kramer, J.Zunft & P.M. Zerwas
Physics Letters B 306 (1993) 371

- D^* tagging: $\mathrm{D}^{*\pm} \to \mathrm{D}^0\pi^\pm$
  (TPC/2γ, TASSO, JADE, TOPAZ, AMY, ALEPH)
- Semileptonic decays: $\mathrm{c} \to \mathrm{s}\ \mathrm{W}^*$
  $\hookrightarrow \ell + \nu$
  (TOPAZ,AMY,VENUS)

The L3 Detector



Excellent resolution for e, μ, γ measurements

Hadronic Two-Photon Selection

- $W_{vis} > 3$ GeV reduces light quark $\gamma\gamma$ bkg
- $E_{total}/\sqrt{s} < 0.38$ removes single γ ann.
- $N_{tracks} \geq 5$ removes $\ell^+\ell^-$ bkg
- $E_{Lumi}/E_{Beam} < 0.4$ anti-tag condition

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	Events	BKG (%)
91	80	93204	2.4
136	12	21045	0.2
167	21	44444	0.2
183	52	116760	0.2
189	176	399755	0.1

❒ MC: PYTHIA version 5.722

$e^+e^- \to e^+e^-q\bar{q}$

LO Calculations with $W_{gen} > 3$ GeV

❒ $\mathcal{L}_{\gamma\gamma}$ EPA ($Q^2 < 1$ GeV)

Real Photons

❒ Background Sources

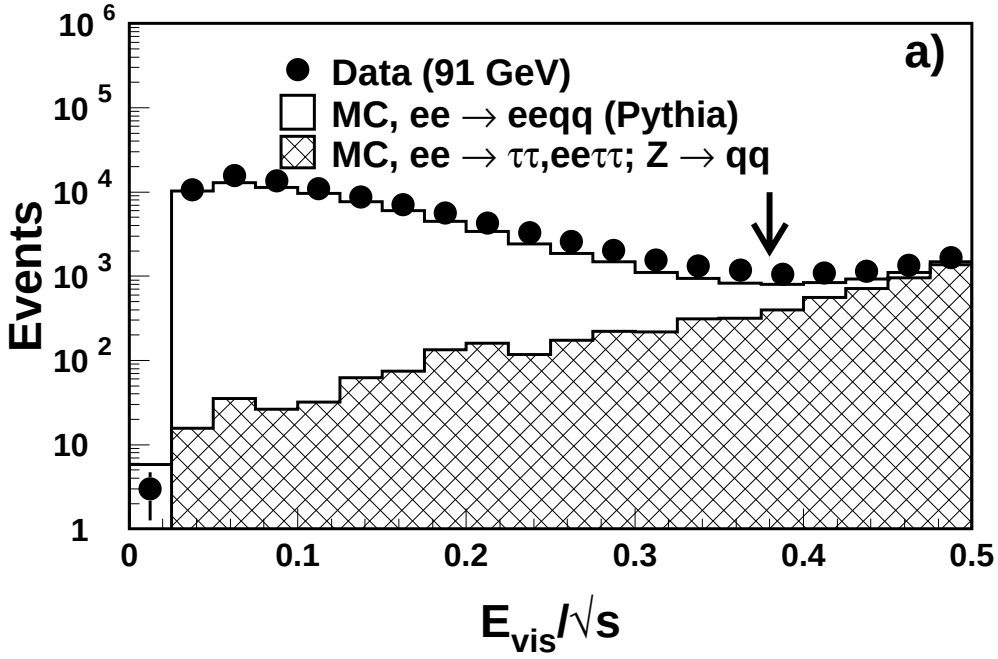
$e^+e^- \to Z/\gamma \to q\bar{q}$ (JETSET/PYTHIA)

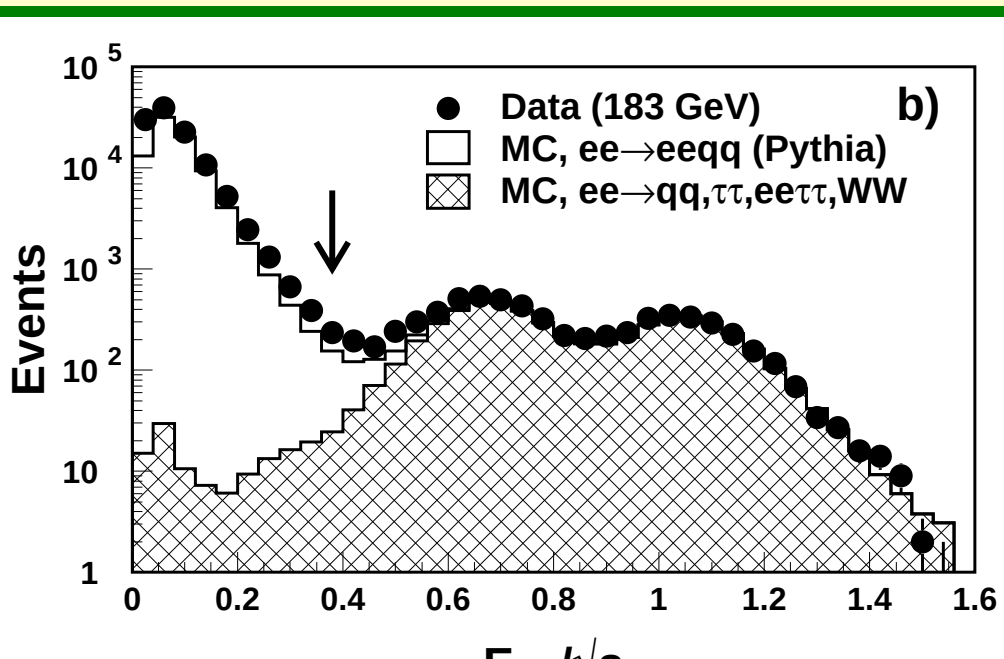
$e^+e^- \to \tau^+\tau^-$ (KORALZ)

$e^+e^- \to W^+W^-$ (KORALW)

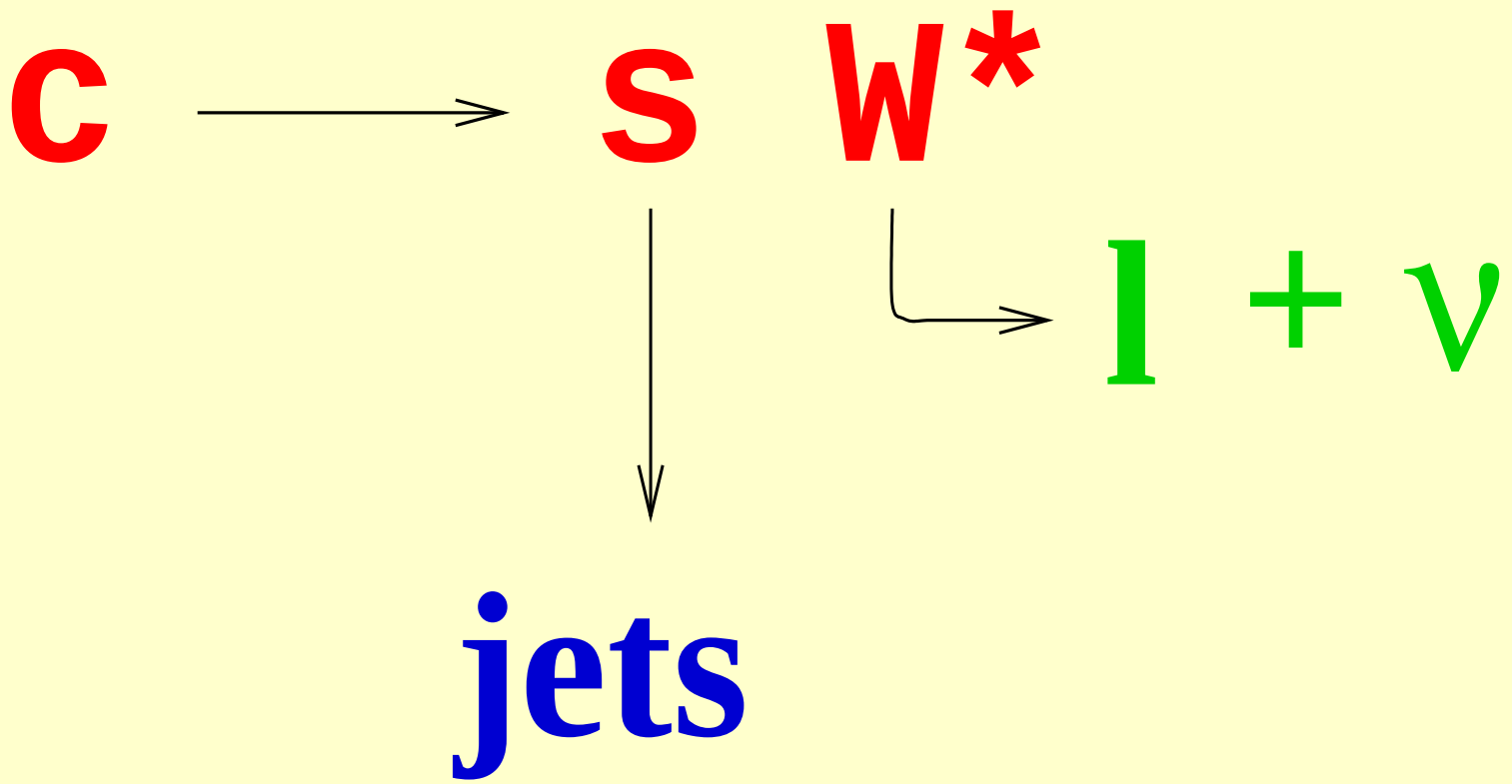
$e^+e^- \to e^+e^-\tau^+\tau^-$ (DIAG36)

Hadronic Two-Photon Selection





Semi-Leptonic Decay of Charm



Lepton Selection

Muon Selection

$|\cos\theta| < 0.90$

$P_\mu > 2$ GeV

$P_\mu < 0.2\ E_{Beam}$

Electron Selection

$|\cos\theta| < 0.90$

$E_e > 0.6$ GeV

$\Delta\phi < 20$ mrad

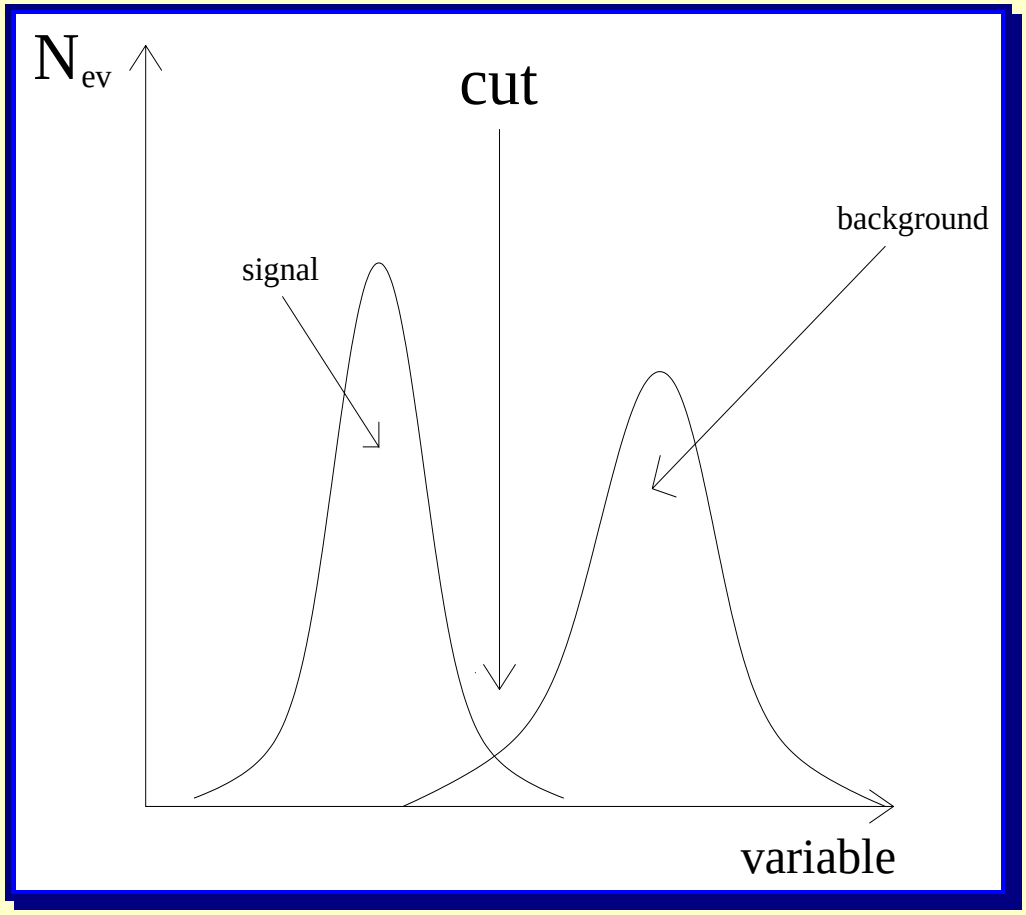
$|DCA| < 0.5$ mm

$\chi^2_{EM} < 3$

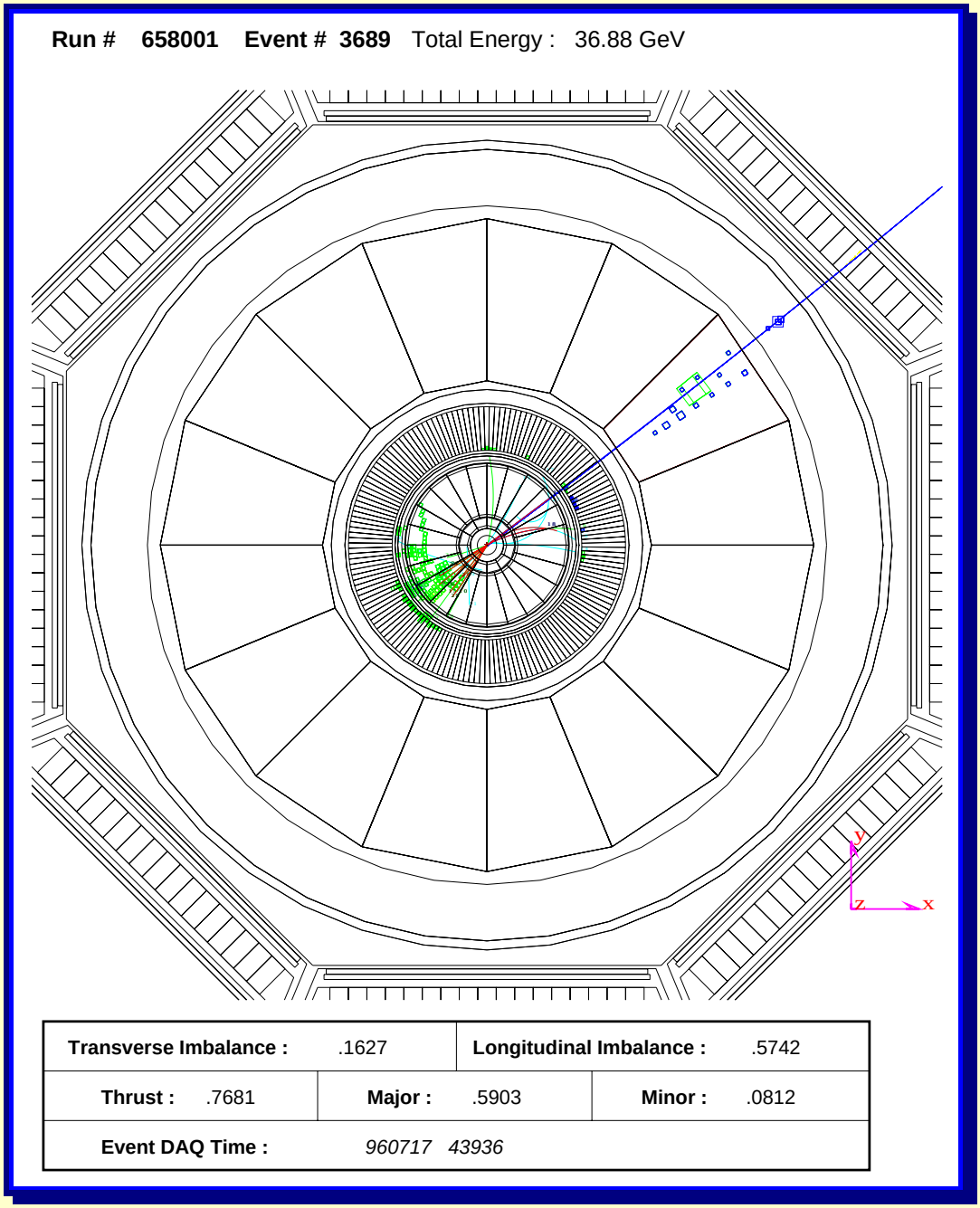
$E_1/E_9 > 0.5$

$E_9/E_{25} > 0.95$

$0.85 < E_T/p_T < 1.2$



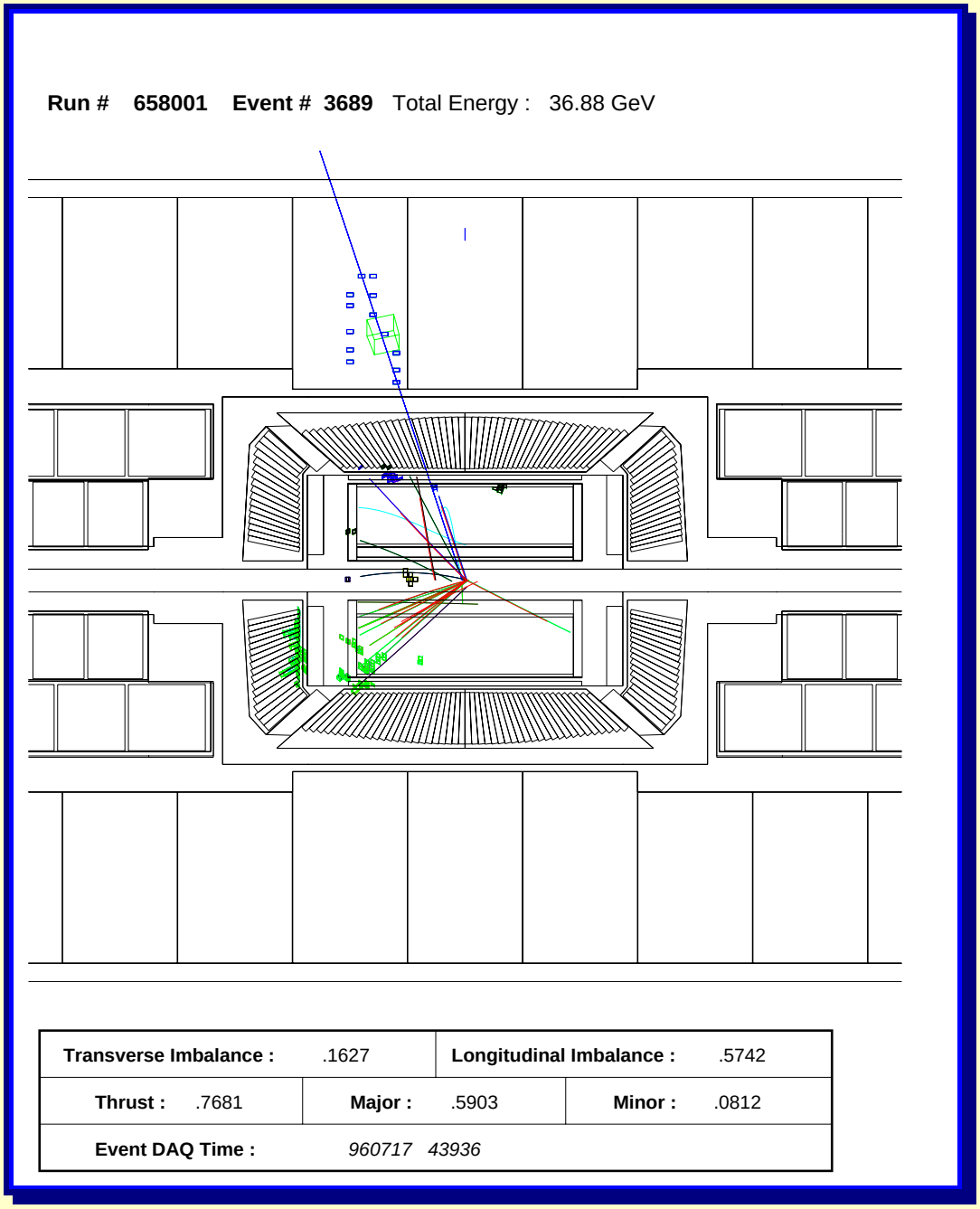
Muon Candidate



Transverse Imbalance :	.1627		**Longitudinal Imbalance :**	.5742	
Thrust :	.7681	**Major :**	.5903	**Minor :**	.0812
Event DAQ Time :	*960717 43936*				

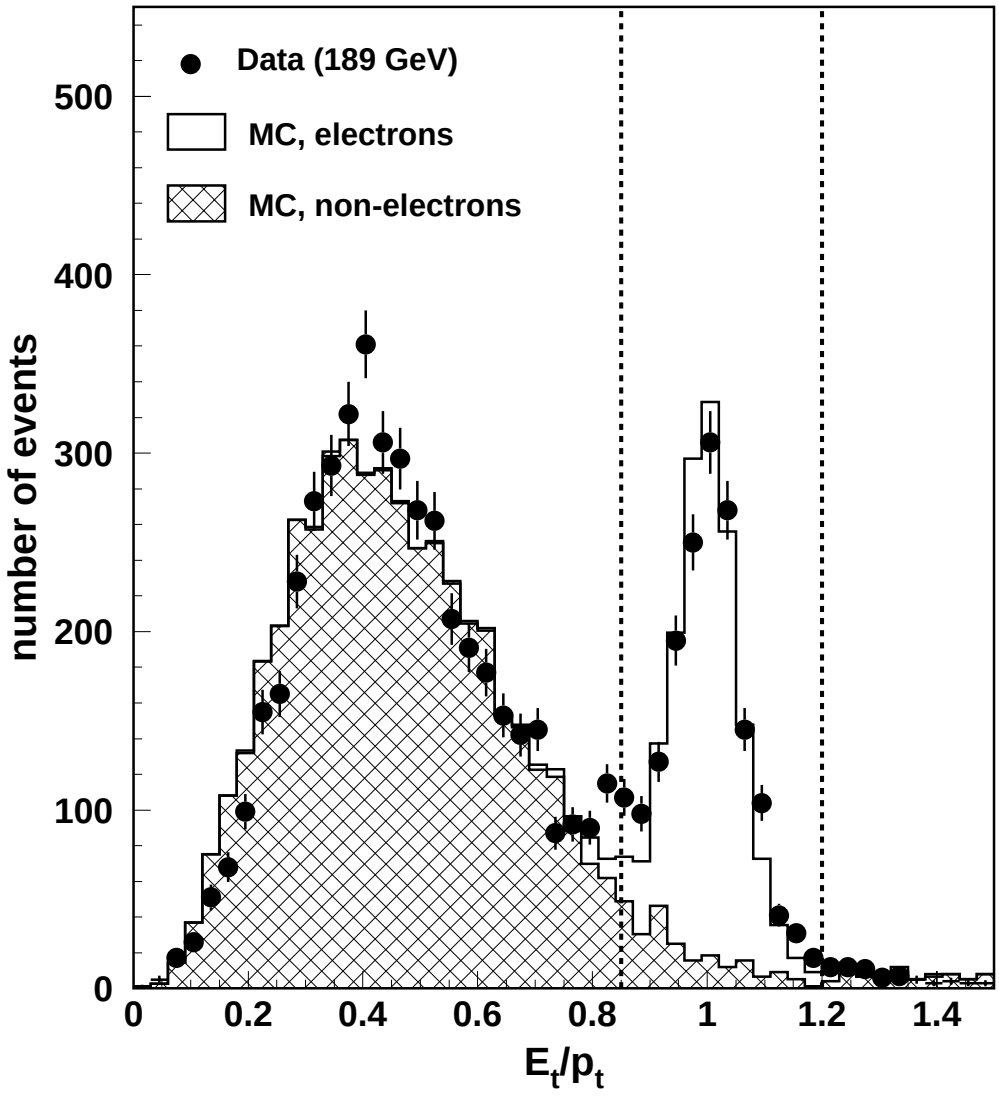
Transverse view of a two-photon muon-tagged event

Muon Candidate



Longitudinal view of a two-photon muon-tagged event

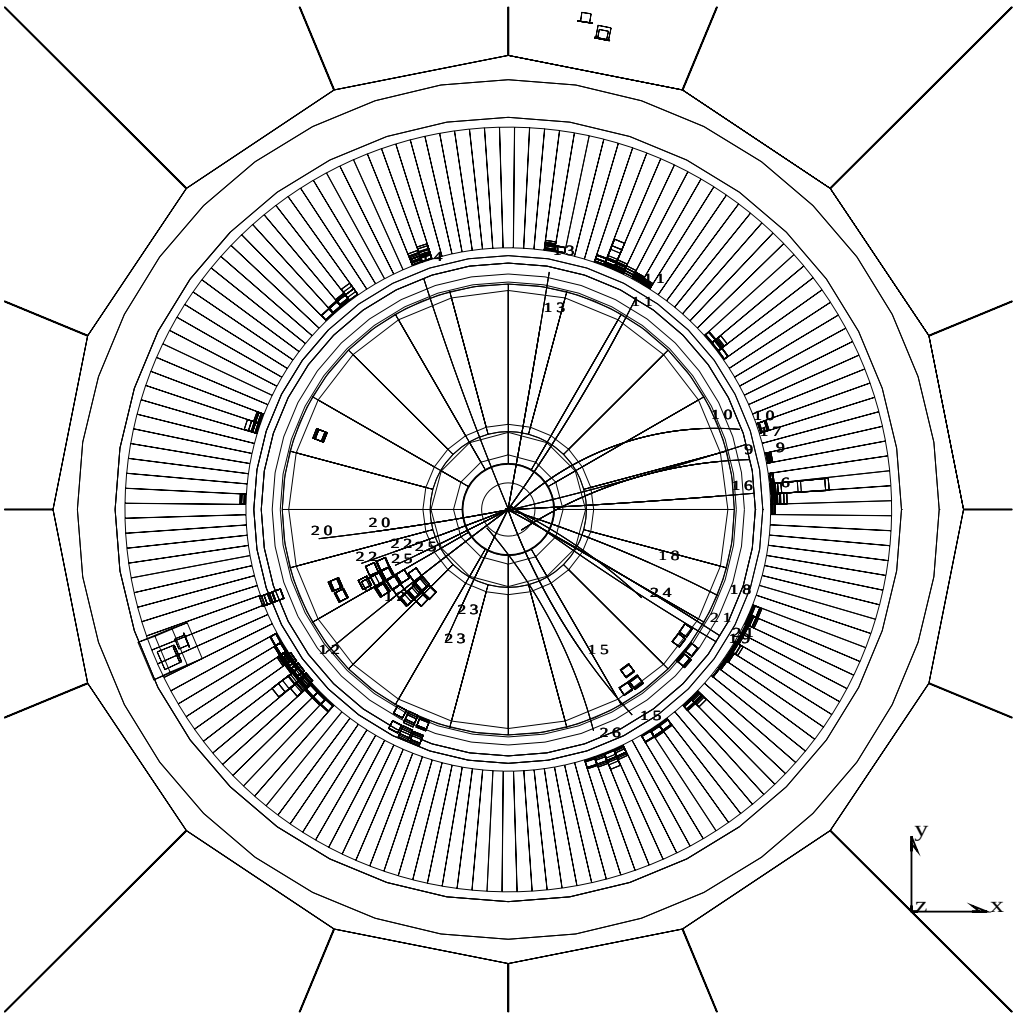
Electron Selection



1710 events; electron purity 85%.

Electron Candidate

Run # 688501 Event # 1069 Total Energy : 29.94 GeV



Transverse Imbalance :	.0453		**Longitudinal Imbalance :**	-.5303	
Thrust :	.7080	**Major :**	.4463	**Minor :**	.3052
Event DAQ Time :	*971027 145523*				

Transverse view of a two-photon electron-tagged event
p = 2.3 GeV and $\phi = 3°$

Lepton Selection Summary

Electrons

$\sqrt{s}$	N_{OBS}	N_{EXP}	N_{BKG}	N_{conv}	P_e	ϵ_e
91	282	252	29.5	37.1	0.84	0.097
136	82	45	0.5	8.4	0.84	0.084
167	156	112	1.5	22.8	0.85	0.096
183	433	273	4.1	50.5	0.86	0.100
189	**1710**	**892**	**14.7**	**199.4**	**0.86**	**0.100**

Muons

$\sqrt{s}$	N_{OBS}	N_{EXP}	N_{BKG}	P_μ	ϵ_μ
91	57	45	16.9	1.00	0.33
167	16	15	1.4	1.00	0.33
183	52	39	1.4	1.00	0.33
189	**208**	**185.3**	**17.9**	**0.94**	**0.33**

- N_{BKG}: **Background from annihilation processes and two-photon production of tau pairs**
- N_{conv}: **Electrons from photon conversions**
- P_e (P_μ): **Electron (Muon) purity**
- ϵ_e (ϵ_μ): **Electron (Muon) selection efficiency**

Inclusive Charm Cross Section

$$e^+e^- \to e^+e^- c\bar{c}X$$

$$\sigma = \frac{(N^{lept}_{obs} - N^{lept}_{bkg})\ \pi_c}{\mathcal{L}\ \epsilon_{trig}\ \epsilon'_c}$$

$$\pi_c = \frac{N^{lept}_c}{N^{lept}_c + N^{lept}_{nc}}$$

..to be less dependent on Monte Carlo flavor composition (charm and non-charm)...

$$\pi_c = (1 - \frac{\epsilon_{nc}}{\epsilon_d})/(1 - \frac{\epsilon_{nc}}{\epsilon_c})$$

$$\epsilon_d = \frac{N^{lept}_c + N^{lept}_{nc}}{N^{had}_c + N^{had}_{nc}} = \frac{N^{lept}_{obs} - N^{lept}_{bkg}}{N^{had}_{obs} - N^{had}_{bkg}}$$

$$\frac{N^{lept}_c + N^{lept}_{nc}}{\epsilon_d} = \frac{N^{lept}_c}{\epsilon_c} + \frac{N^{lept}_{nc}}{\epsilon_{nc}}$$

had : after hadronic two-photon selection
lept: after final selection with lepton tag

Charm Analysis Summary

Electron Tag

$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]	N^e_{obs} Events	N^e_{bkg} Events	π^e_c [%]	$\epsilon^{e\prime}_c$ [10^{-2}%]
91	79.8	282	29.5	50.5 ± 4.9	42.2 ± 3.4
136	12.1	82	0.5	70.0 ± 3.4	42.0 ± 4.0
167	21.2	156	1.5	60.0 ± 3.2	52.6 ± 3.3
183	52.2	433	4.1	65.9 ± 2.2	53.3 ± 2.6
189	**176.**	**1710**	**14.7**	$\mathbf{66.6 \pm 1.6}$	$\mathbf{46.0 \pm 1.8}$

Muon Tag

$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]	N^μ_{obs} Events	N^μ_{bkg} Events	π^μ_c [%]	$\epsilon^{e\prime}_c$ [10^{-2}%]
91	79.8	57	15.9	70.6 ± 8.8	6.43 ± 1.10
167	21.2	16	1.41	48.3 ± 10.1	6.48 ± 1.01
183	52.2	52	1.38	61.7 ± 6.8	5.59 ± 0.83
189	**176.**	**208**	**17.9**	$\mathbf{63.8 \pm 6.7}$	$\mathbf{6.93 \pm 0.49}$

Inclusive Charm Cross Section

❒ $e^+e^- \to e^+e^-c\bar{c}$ (**Electron Tag**)

$$\sigma_{91\ \mathrm{GeV}} = 435 \pm 64\ (\mathrm{stat}) \pm 76\ (\mathrm{syst})\ \mathrm{[pb]}$$

$$\sigma_{136\ \mathrm{GeV}} = 1358 \pm 243\ (\mathrm{stat}) \pm 180\ (\mathrm{syst})\ \mathrm{[pb]}$$

$$\sigma_{167\ \mathrm{GeV}} = 1009 \pm 152\ (\mathrm{stat}) \pm 106\ (\mathrm{syst})\ \mathrm{[pb]}$$

$$\sigma_{183\ \mathrm{GeV}} = 1291 \pm 105\ (\mathrm{stat}) \pm 122\ (\mathrm{syst})\ \mathrm{[pb]}$$

$$\sigma_{189\ \mathrm{GeV}} = 1599 \pm 60\ (\mathrm{stat}) \pm 174\ (\mathrm{syst})\ \mathrm{[pb]}$$

❒ $e^+e^- \to e^+e^-c\bar{c}$ (**Muon Tag**)

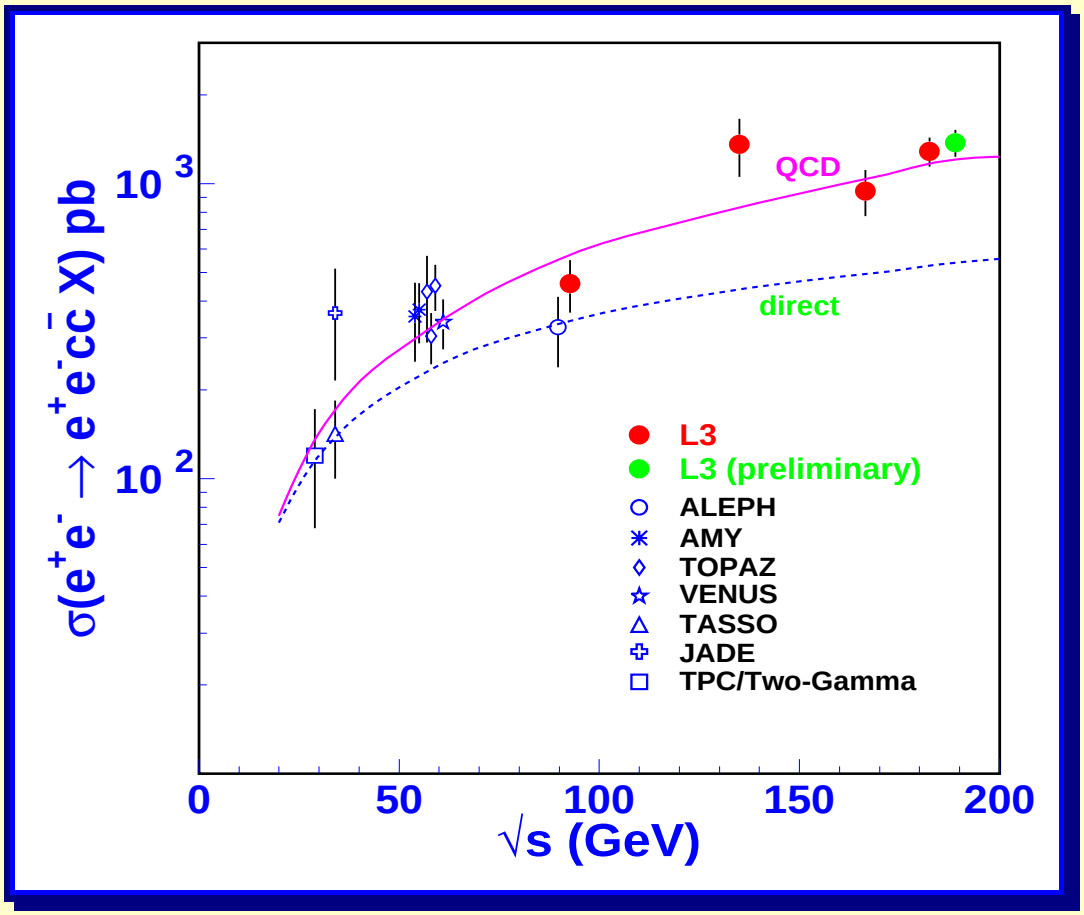
$$\sigma_{91\ \mathrm{GeV}} = 601 \pm 168\ (\mathrm{stat}) \pm 75\ (\mathrm{syst})\ \mathrm{[pb]}$$

$$\sigma_{167\ \mathrm{GeV}} = 576 \pm 361\ (\mathrm{stat}) \pm 197\ (\mathrm{syst})\ \mathrm{[pb]}$$

$$\sigma_{183\ \mathrm{GeV}} = 1260 \pm 328\ (\mathrm{stat}) \pm 246\ (\mathrm{syst})\ \mathrm{[pb]}$$

$$\sigma_{189\ \mathrm{GeV}} = 1070 \pm 144\ (\mathrm{stat}) \pm 152\ (\mathrm{syst})\ \mathrm{[pb]}$$

Total Inclusive Charm Cross Section



PL B453 88 (1999)

$$e^+e^- \to e^+e^- c\bar{c}X$$

$\sigma_{91\ \mathrm{GeV}} = 459 \pm 60\ \text{(stat)} \pm 75\ \text{(syst)}\ \text{[pb]}$

$\sigma_{136\ \mathrm{GeV}} = 1358 \pm 243\ \text{(stat)} \pm 180\ \text{(syst)}\ \text{[pb]}$

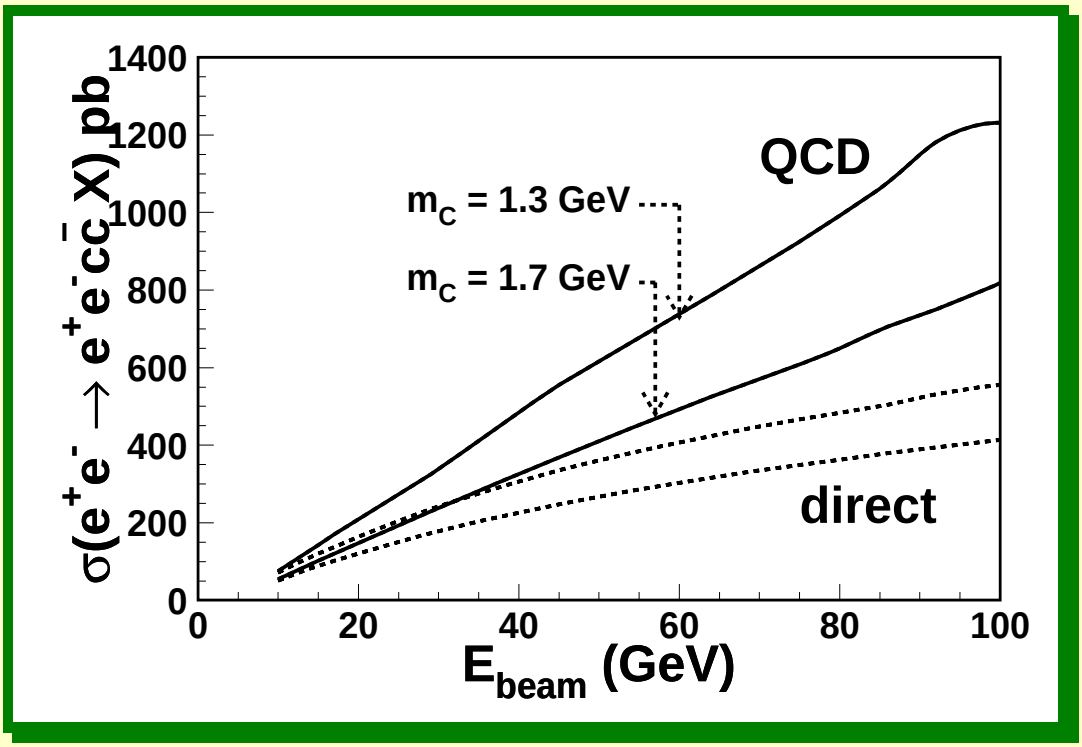
$\sigma_{167\ \mathrm{GeV}} = 936 \pm 140\ \text{(stat)} \pm 100\ \text{(syst)}\ \text{[pb]}$

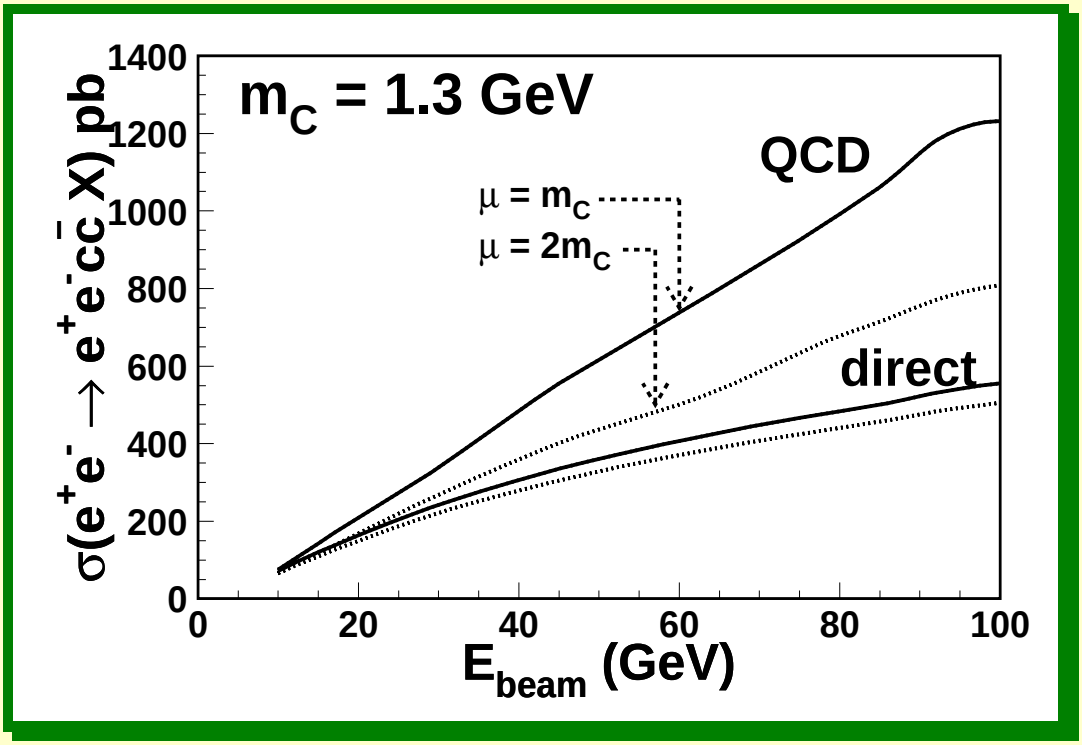
$\sigma_{183\ \mathrm{GeV}} = 1287 \pm 100\ \text{(stat)} \pm 114\ \text{(syst)}\ \text{[pb]}$

$\sigma_{189\ \mathrm{GeV}} = 1378 \pm 55\ \text{(stat)} \pm 134\ \text{(syst)}\ \text{[pb]}$

Prediction is calculated using $m_c = 1.3$ GeV
Renormalization scale chosen to be the charm mass

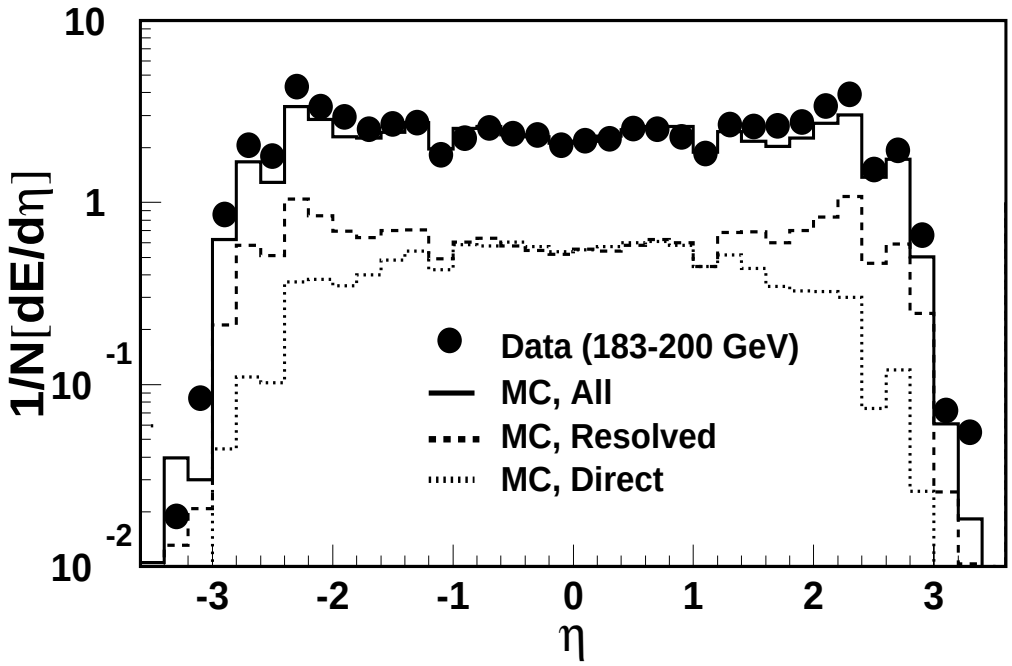
Charm Quark Mass





Direct & Resolved Contributions

Energy flow as function of pseudorapidity



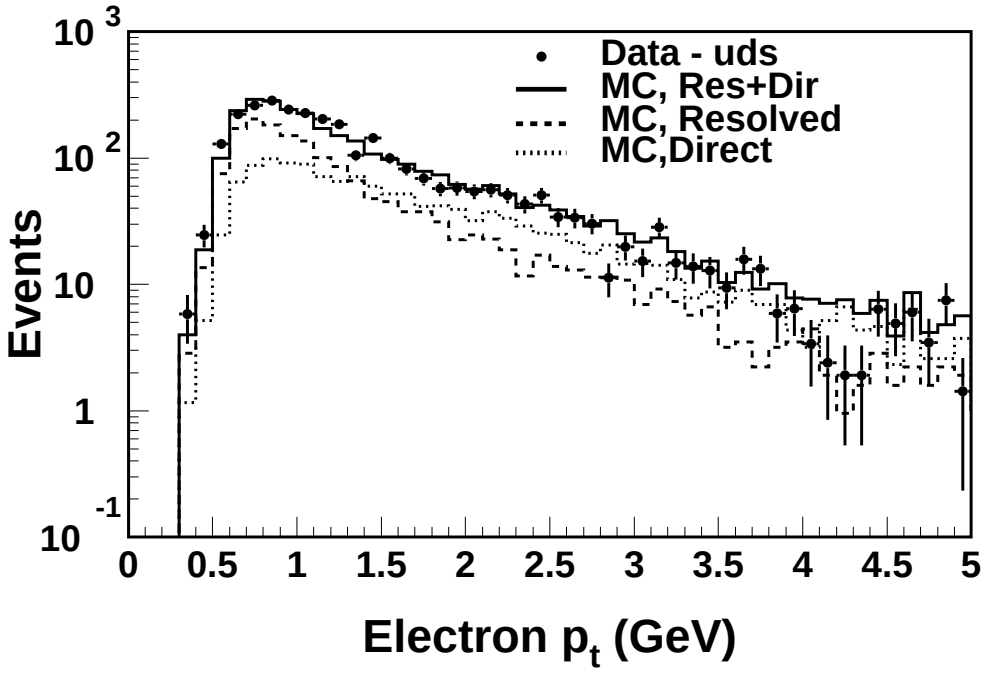
$$\eta = -\ln[\tan(\frac{\theta}{2})]$$

- $\eta = 1.0 \Longrightarrow \theta \simeq 40^\circ$
- $\eta = 1.5 \Longrightarrow \theta \simeq 25^\circ$
- $\eta = 2.0 \Longrightarrow \theta \simeq 15^\circ$

Resolved process has small angle remnant jet
Need resolved to describe the data

Direct & Resolved Contributions

Transverse momentum of Electron candidate

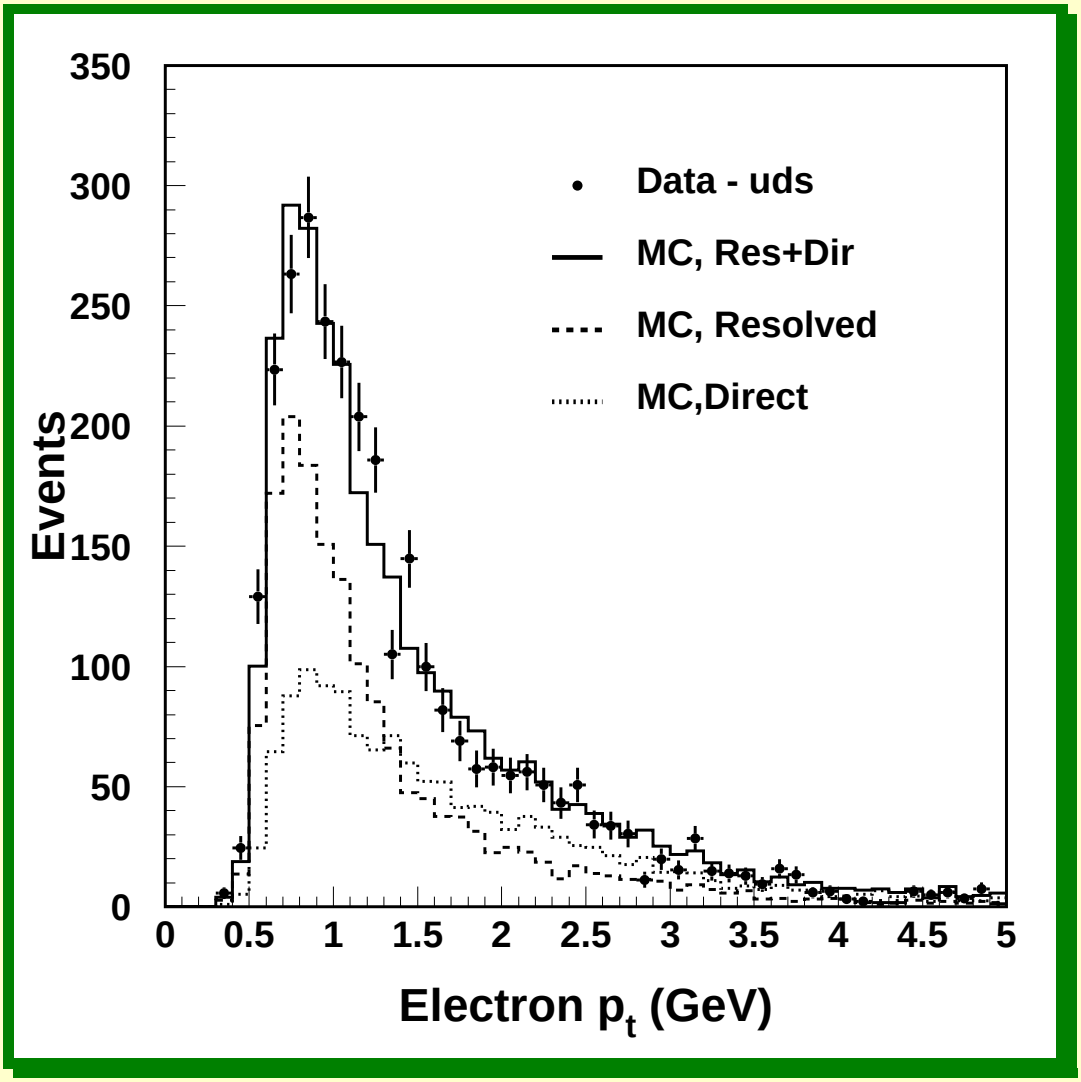


- MC prediction for non-charm (uds) subtracted from the data
- Resolved and direct MC predictions normalized to final number of data - uds events

two-thirds Resolved & one-third Direct

Direct & Resolved Contributions

Transverse momentum of Electron candidate



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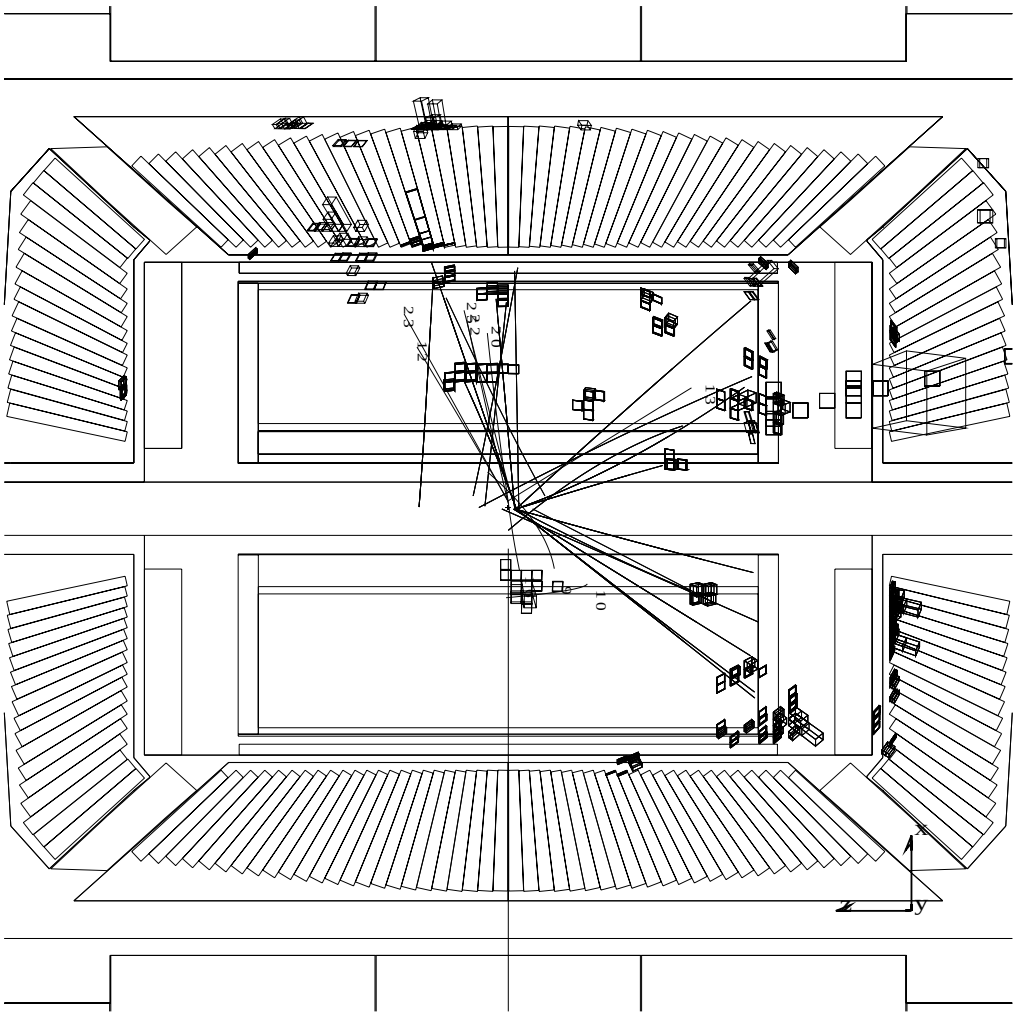
Electron Candidate

Run # 688501 Event # 1069 Total Energy : 29.94 GeV



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Thrust :	.7080	**Major :**	.4463	**Minor :**	.3052
Event DAQ Time :	*971027 145523*				

Longitudinal view of a two-photon electron-tagged event

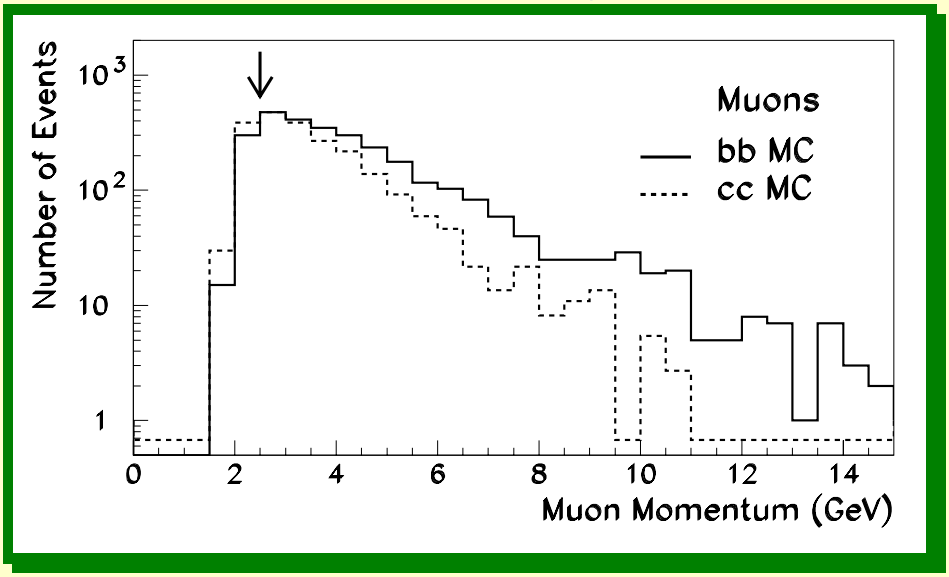
3 jets: Resolved remant or Gluon Radiation

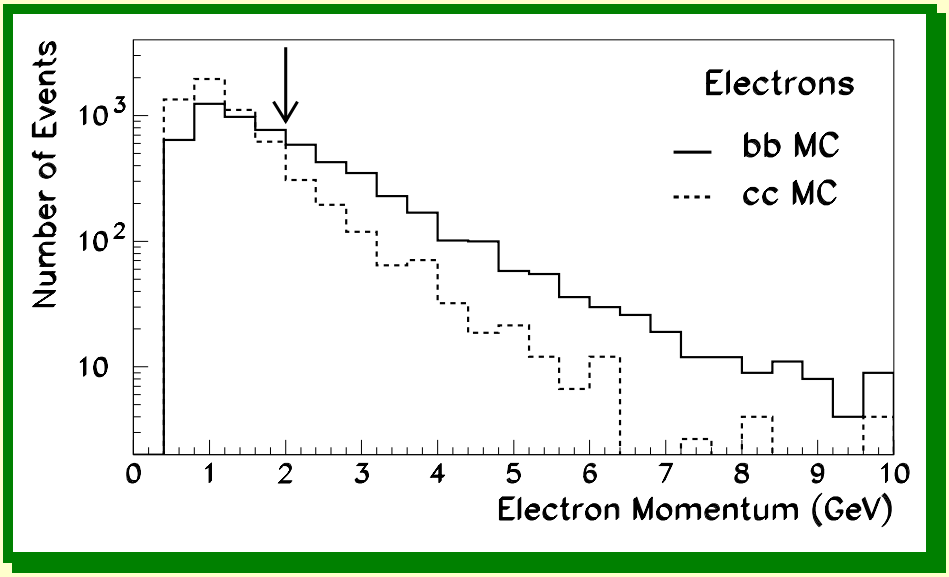
p = 2.3 GeV and $\theta = 73^\circ$

Search for Beauty

Tag b by semi-leptonic decay to e or μ

Momentum of Lepton Candidate
from the Monte Carlo

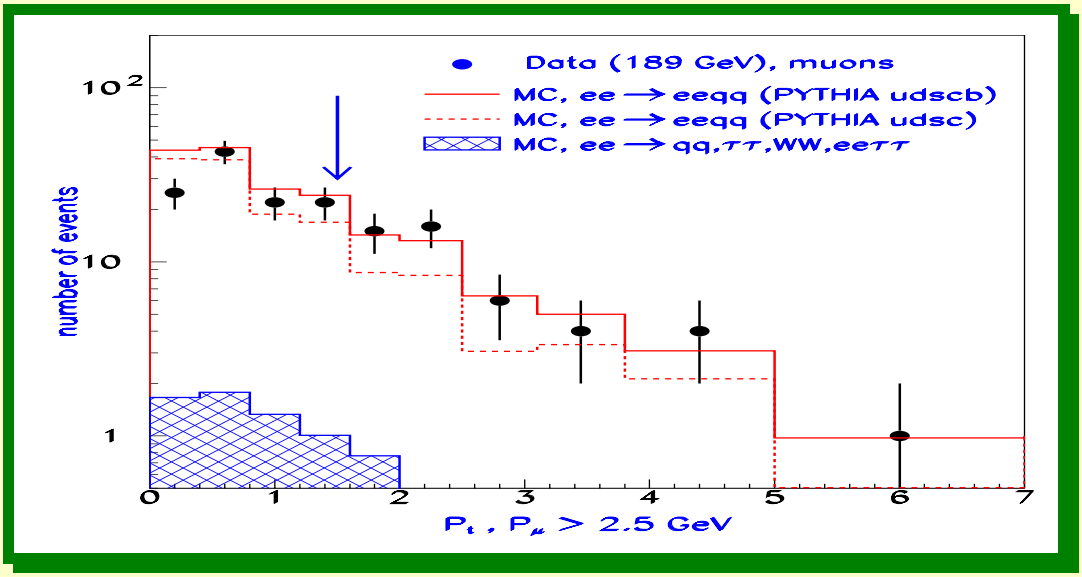


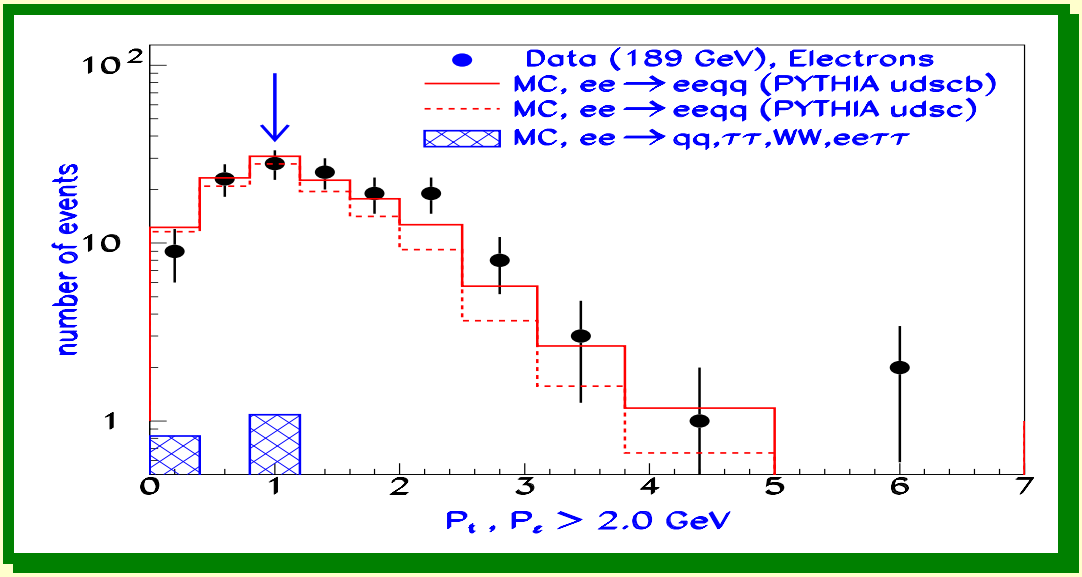


Leptons from beauty decays have higher momentum
than from charm

Search for Beauty

p_t with respect to the nearest jet



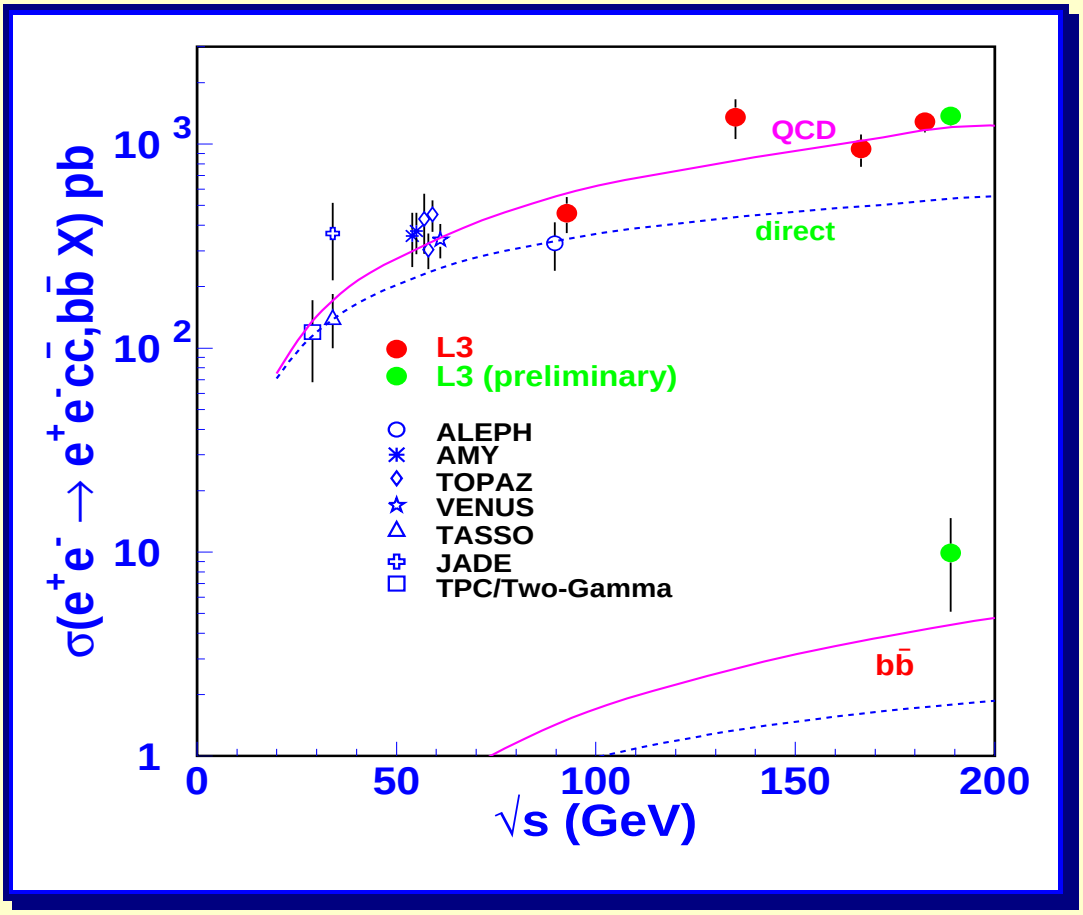


$\mathbf{P_t}$ >1.5 GeV	$\mathbf{P_t^e}$ >1 GeV
$\mathbf{N_{ev}^{\mu} = 49}$	$\mathbf{N_{ev}^{e} = 96}$
ε_b^{μ} =0.9%	ε_b^{e} =1.6%
$\mathbf{\Pi_b^{\mu}}$ =34%	$\mathbf{\Pi_b^{e}}$ =28%

Leptons from beauty decays have higher p_t

Beauty Production

Preliminary measurement at $\sqrt{s} = 189$ GeV



$$e^+e^- \to e^+e^-b\bar{b}X$$

Muons:	$\sigma_{b\bar{b}}$ =10.3	4.6(stat)	3.3 (syst) pb
Electrons:	$\sigma_{b\bar{b}}$ = 9.6	3.6(stat)	4.1 (syst) pb
Combined:	$\sigma_{b\bar{b}}$ = 9.9	2.9(stat)	3.8 (syst) pb

- Theory prediction from M. Drees,M. Krämer,J. Junft and P.M. Zerwas,PL **B306** 371 (1993)
  $m_c = 1.3$ **GeV**, $m_b = 5.0$ **GeV.**

D* Production in $\gamma\gamma$ Collisions

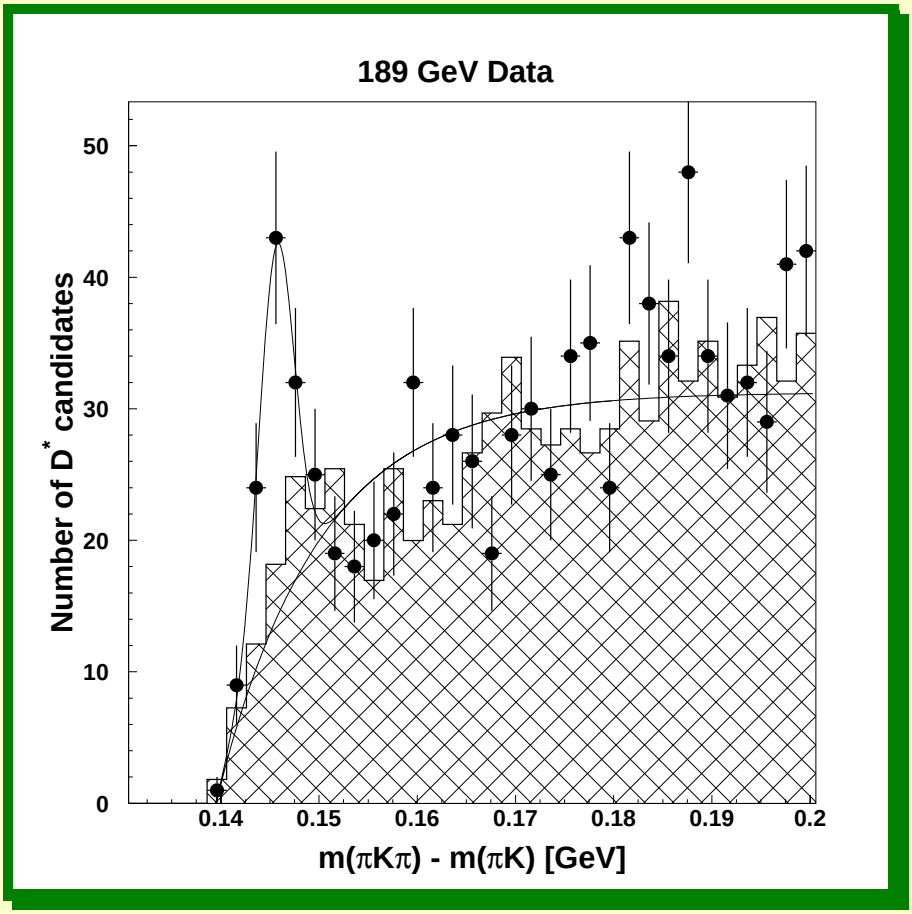
Search for $D^{*\pm} \to D^0\pi_s^\pm \to (K^\mp\pi^\pm)\pi_s^\pm$

Selection:

1: Select hadronic two-photon events

2: π_s: momentum and vertex cuts

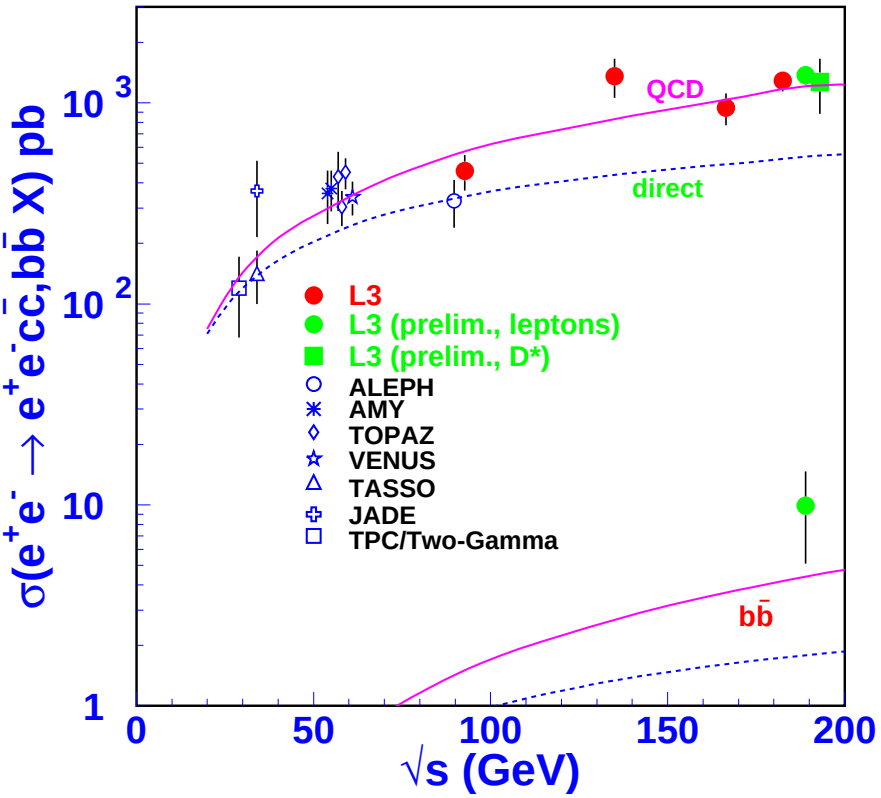
3: D^0: 2 tracks (compatible with $K^\pm\pi^\mp$ by dE/dx)
Select window for D^0 mass: $1.8 < M_{K\pi} < 1.93$



Signal Events: 66±10 $\quad \varepsilon_{D^*}$ =0.049% $\quad \Pi_{D^*}$ =70%

D* Production in $\gamma\gamma$ Collisions

$$\sigma = \frac{N_{obs}^{D^{*\pm}}}{\mathcal{L}\ \epsilon_{trig}\ \epsilon_{D^{*\pm}}\ 2\ P(c \to D^{*+})}$$



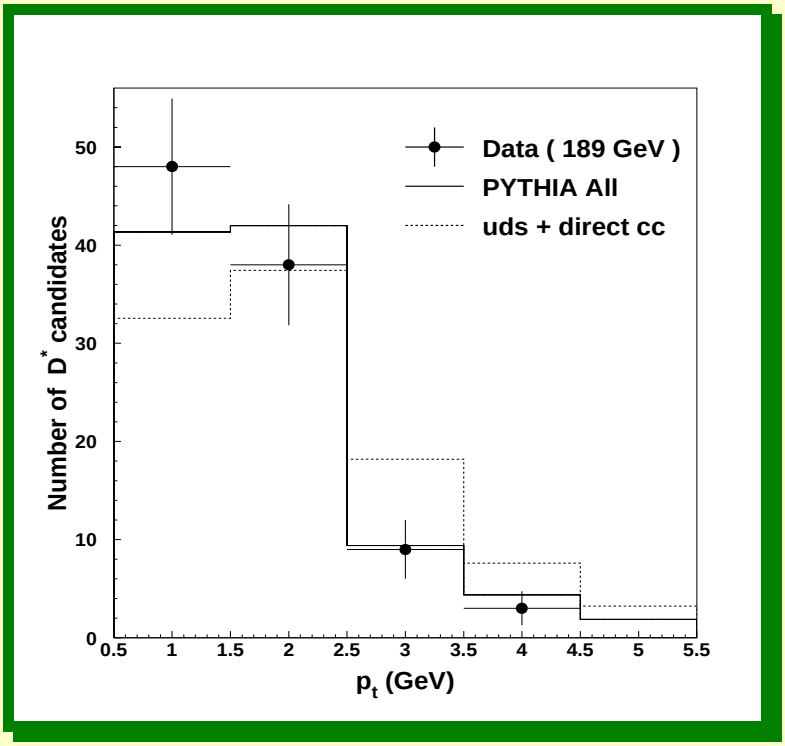
Preliminary Result at $\sqrt{s} = 189$ GeV

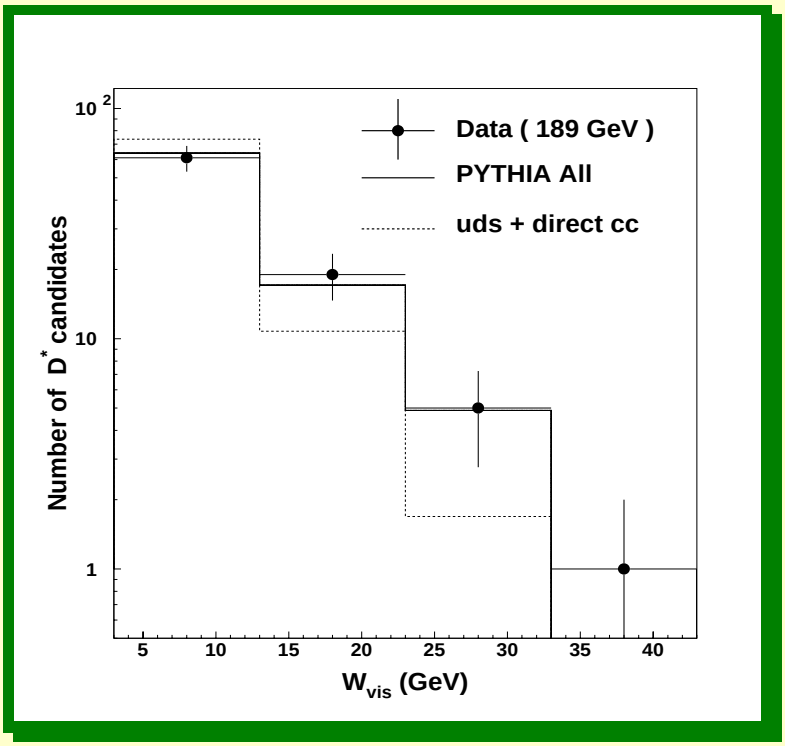
$\sigma = 1269 \pm 185$ (stat) ± 343 (syst) pb

D* result consistent with lepton tags and QCD

D* Production in $\gamma\gamma$ Collisions

L3 Preliminary





Summary

- Measured $\sigma(e^+e^- \to e^+e^- c\bar{c}X)$ in the center-of-mass range of $91\ \mathrm{GeV} \leq \sqrt{s} \leq 189\ \mathrm{GeV}$
- Cross section $\Uparrow$ with $\sqrt{s}$ as expected by QCD prediction
- Direct process, even with real and virtual gluon corrections, is insufficient to describe the data. Need resolved processes
  $\Longrightarrow$ Data require a significant gluon content in the photon
- Direct contribution to cross section dependent only on the charm mass. Perform fit on p_t, visible mass and jets.
- Measured beauty production for first time in $\gamma\gamma$ collisions at $\sqrt{s} = 189$ GeV. Consistent with QCD.
- Unfolding $\gamma\gamma$ cross section for charm
- More data... $\mathcal{L} > 200\ pb^{-1}$ in 1999 alone, with $\sqrt{s} \simeq 202\ GeV$.

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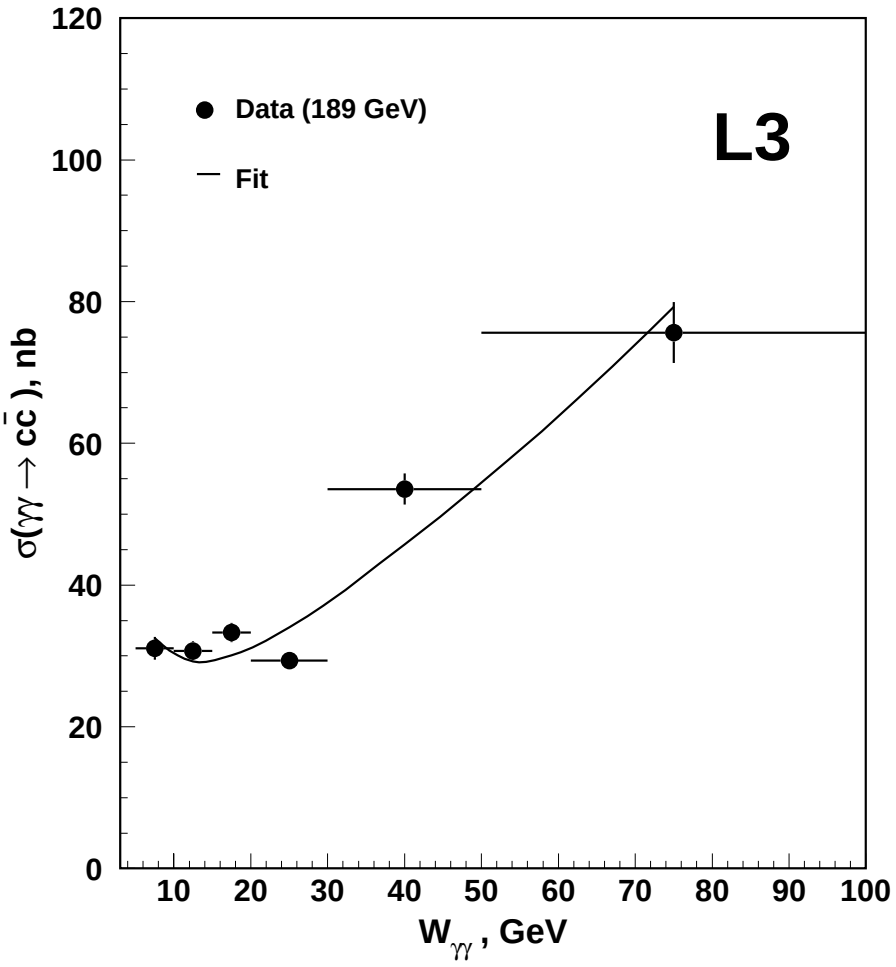
Louisiana State University

$\sigma(\gamma\gamma \to c\bar{c})$

L3 Preliminary

$W_v is > 5\ GeV$



Observed slope rises more quickly with energy than expected universal Regge behavior of total hadronic crosss section